

## Typhoon Impacts and Student Support

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### LONG-TERM GOALS

I seek to understand the interactions between the ocean and tropical cyclones including typhoons and hurricanes.

### OBJECTIVES

These grants support efforts in the TC10/ITOP (Tropical Cyclone 2010 / Impacts of Typhoons on the Ocean in the Pacific) program. This program, joint between ONR and Taiwanese investigators, studied the ocean response to typhoons in the western Pacific Ocean in 2010. ITOP focused on the following scientific questions:

- *How does the cold wake of a typhoon form and dissipate?*

Typhoons produce a complex three-dimensional response of the underlying ocean including strong surface currents, upwelling of the thermocline, intense mixing across the thermocline, the radiation of near-inertial internal waves and the formation of a cold wake behind the storm. The cold wake persists for at least several weeks after the typhoon passage, with a combination of solar heating, lateral mesoscale stirring, lateral mixing by baroclinic instability and continued vertical mixing determining the rate and character of wake dissipation. The wake is also expected to modify the atmospheric boundary layer and the biology and chemistry of the upper ocean, particularly pCO<sub>2</sub>. ITOP seeks to measure the ocean response in detail, with particular emphasis on the mechanisms of cold wake formation and dissipation, and to compare these measurements with model results.

- *What are the air-sea fluxes for winds greater than 30 m/s ?*

Tropical cyclones draw their energy from the underlying warm ocean. Their intensity depends on the exchanges with the ocean; a greater flux of heat and moisture to the storm leads to a stronger storm, but a larger drag on the ocean leads to a weaker storm. These exchanges are poorly parameterized in existing typhoon forecast models leading to errors in the ability of these models to predict typhoon intensity. The first reliable estimates of the exchange coefficients at these high wind speeds, made during the last decade, have shown a dramatic decrease in drag coefficient relative to previous parameterizations. ITOP seeks to make additional measurements, at higher wind speeds and under a larger variety of conditions.

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- *How do ocean eddies affect typhoons and the response to typhoons?*

Ocean mesoscale eddies are expected to modulate the ocean response to typhoons by varying the depth of the pycnocline and thus the intensity and location of the cold wake. This, in turn, will change the air-sea fluxes and thus the intensity of the typhoon. Thus warm eddies act as typhoon boosters, by limiting the amount of cooling in the wake and cold eddies act as typhoon damps. ITOP seeks to study these interactions in detail.

- *What is the surface wave field under typhoons ?*

The air-sea exchange depends critically on the state of the ocean surface, most importantly characterized by the surface waves. The wave fields beneath typhoons are complex, with multiple dominant wave directions varying and interacting across the different storm quadrants. Modern coupled air-sea models of tropical cyclones include explicit models of the wave fields from which the air-sea exchange rates are computed. More practically, the enormous surface waves produced by typhoons are of great interest in themselves. ITOP seeks to measure the surface wave field underneath typhoons, to compare these measurements with models and to assess their impact on air-sea exchange and remote sensing signatures.

- *How is typhoon genesis related to environmental factors?*

Over the tropical western North Pacific, the monsoon environment contains favorable large-scale conditions related to tropical cyclone formation and intensification. The monsoon and tropical cyclone activity vary in response to multiple synoptic-scale and intraseasonal phenomena such as waves in the monsoon trough and the Madden-Julian Oscillation. ITOP seeks to examine how these large-scale environmental factors affect the formation and intensification of tropical cyclones.

- *Typhoon forecasting*

Although the primary aim of ITOP is typhoon research, much of the data gathered by ITOP will be immediately useful for operational forecasting of typhoons. ITOP seeks to make such data available to all regional forecasting organizations and, as much as possible, work with them to improve typhoon forecasting during the experimental period.

## APPROACH

ITOP was a large international program. Details of the program operations are included in my 2011 annual report. This grant supports my role as Chief Scientist in ITOP, the analysis of my own measurements during this project, supervision of Rosalinda Mrvaljevic, a graduate student supported under the Early Student Support grant and temporary supervision of Andy Hsu, a graduate student nominally supported by Ren Chieh Lien, during Ren Cheih's illness. Andy's work is reported in Ren Chieh Lien's annual report.

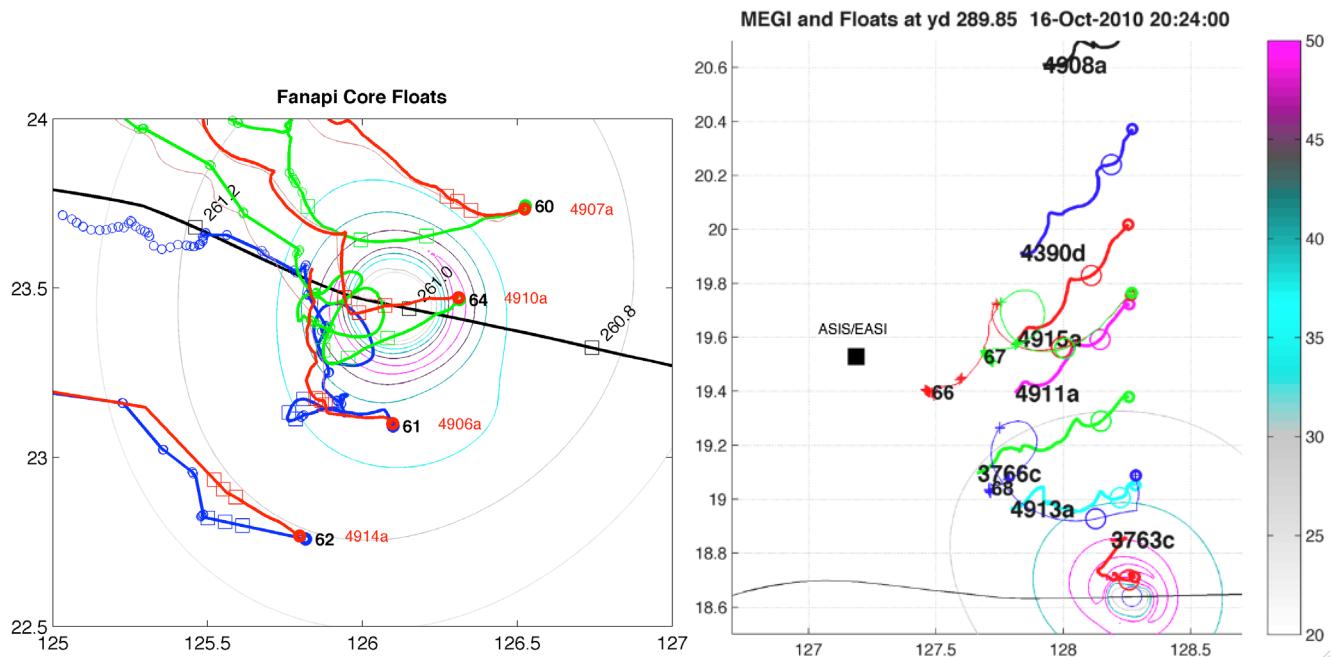
During ITOP, Lagrangian floats were deployed by Air Force C130's: 3 in Typhoon Fanapi and 3 in Typhoon Megi as shown in Fig. 1. The Lagrangian floats are designed to accurately follow the three-dimensional motion of water parcels within the ocean mixed layer while measuring their temperature and salinity. This is accomplished by matching the density of the floats to that of the water surrounding them, as measured by onboard CTDs, so that the net buoyancy of the floats is less than 1g, and by a large vertical drag provided by a folding cloth drogue with approximately  $1 \text{ m}^2$  area. The floats are deployed in specialized air-deployment packages which protect the floats during handling

and deployment from the C130, release the parachute upon water impact and then release the float from the package 20-40 minutes after water entry.

The floats measured pressure, temperature and salinity, thus allowing vertical velocity, vertical kinetic energy and vertical heat and salt fluxes to be estimated. The floats also measured ambient sound (30 Hz – 50 kHz) from which wave breaking rates could be estimated and the difference in pressure between their top and middle, from which surface wave height could be estimated. They thus could relate atmospheric forcing, surface wave properties and ocean boundary layer turbulence under extreme wind and test ocean boundary layer turbulence models.

## WORK COMPLETED

The ITOP Lagrangian floats were embedded in a larger array of EM-APEX floats (also shown in Fig. 1) and surface drifters (not shown). The EM-APEX floats measure velocity; this velocity was used to navigate the floats between the less frequent surface GPS and Iridium fixes, producing the float tracks seen in Fig. 1. Both storms were surveyed by C130 aircraft based in Guam multiple times, with a survey made as each storm passed over the float array. Winds at a height of 10m from the dropsondes deployed by these aircraft and from the onboard SFMR (Stepped Frequency Microwave Radiometer) were used to construct maps of the wind field. These are also shown in Fig. 1. These maps have been distributed to ITOP PIs and used in several other studies of the ocean response to the storms.

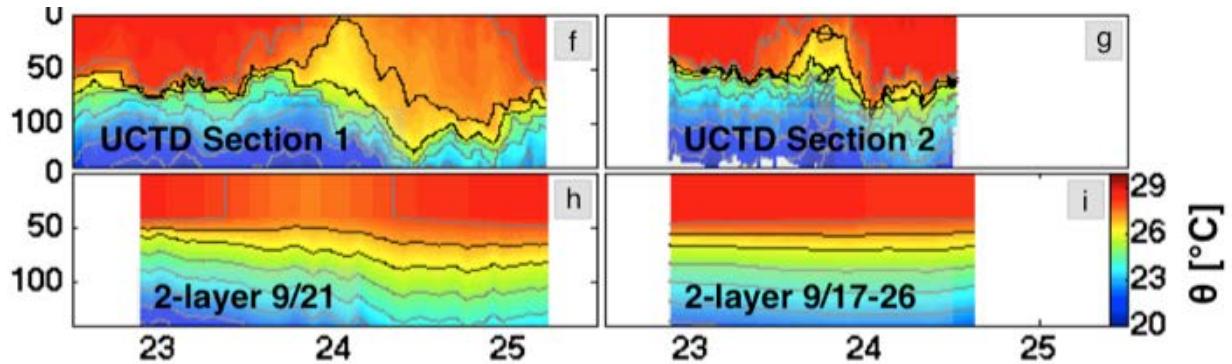


**Figure 1. Trajectories of Lagrangian (60 61 62 64 66 67 68) and EM-APEX (4907 4910 4906 4911 4908 4390 4915 4911 4913 3763) floats deployed in Typhoons Fanapi (left) and Megi (right) as part of ITOP in 2010 superimposed on colored contours of wind speed. Note very much larger size of Fanapi relative to Megi. The location of the ASIS/EASI buoy near Megi is also shown.**

The ambient noise data is relatively large (12 GB) and measures both the noise of the ocean and the various noises made by the float: the pumps on the CTD and other sensors, the opening and closing of the drogue and the motion of the buoyancy piston. Dr. Zhongxiang Zhao at APL has worked to clean these noises from the data and has now produced a clean acoustic data from 7 floats (6 ITOP plus one from Hurricane Gustav) spanning winds from 10-45 m/s and depths from the surface to 40m.

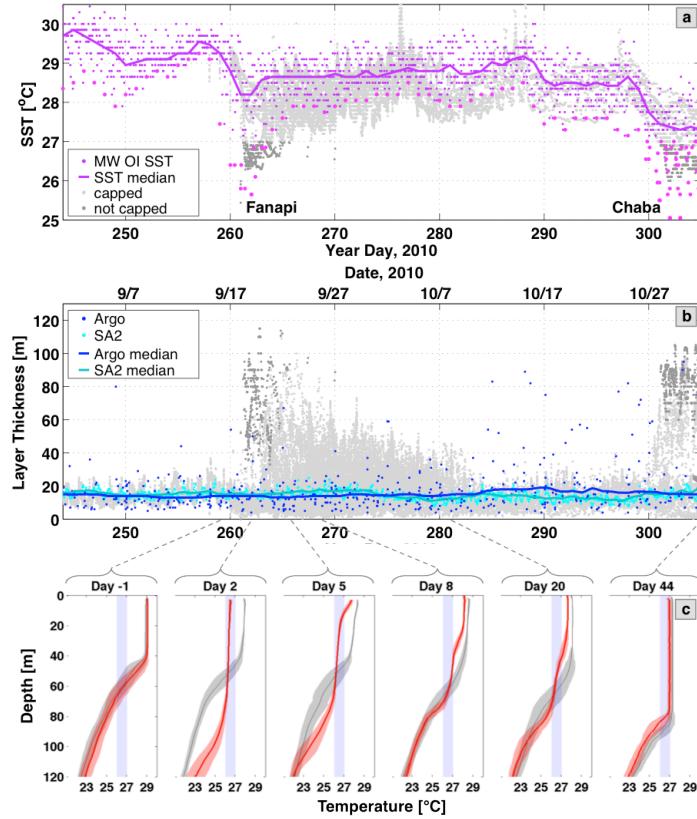
## RESULTS

Rosalinda Mrvaljevic completed her Masters' last year and is working toward her general Exam and on revising the publication of her Masters' work, submitted to GRL. Her collaborative work with I.I. Lin (NTU in Taiwan) has shown that Fanapi's wake is not properly represented in by the two layer models that use altimetry and SST to compute subsurface temperature profiles. This is shown in Fig. 3. The temperature profiles of wakes differ from the typical low-mode fluctuations due to mesoscale eddies, being more like 3-layer, than 2-layer structures, and thus cannot be properly defined from two surface parameters, SST and surface height.



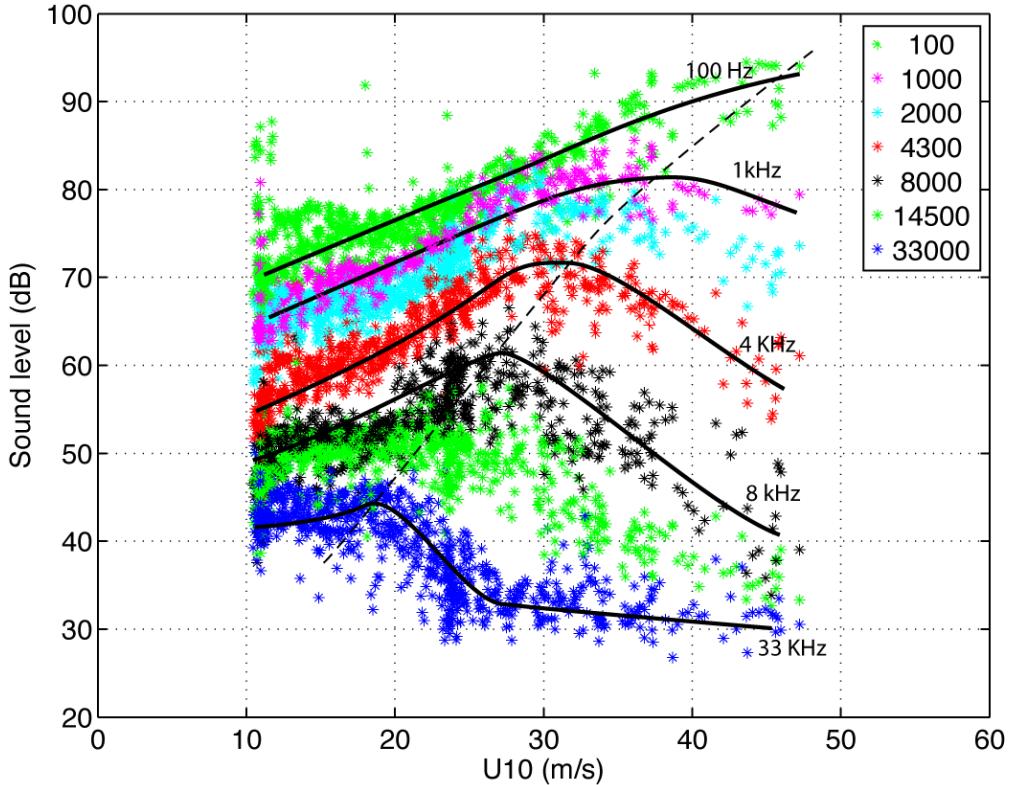
*Figure 2. Comparison of temperature sections across the subsurface wake of Typhoon Fanapi measured by the R.V. Revelle (top panels) and computed from a nearby altimeter line using a two-layer model (bottom panels). The altimeter section does not see the subsurface wake.*

An overview of evolution of Fanapi's wake is seen in Fig. 3 comparing the evolution of SST and subsurface structure. SST cools in a distinctive two phase pattern, first rapidly as the wake is capped by warm water and then more slowly as entrainment into the capped wake keeps the water above the wake cooler than its surroundings.



**Figure 3.** a) Time series of SST in the Fanapi region from microwave SST and the ITOP in situ data. Following Fanapi, rapid warming occurred in the first ~4 days as a thin mixed layer ('cap' with  $T > 27^{\circ}\text{C}$ ) formed over the cold wake. A second, slower warming occurred over the following ~10 days, but the SST cold wake and surrounding region never recovered to pre-Fanapi temperatures before TY Chaba caused widespread cooling in the region. b) Time series of the observed thickness of the  $26^{\circ}\text{C}$  to  $27^{\circ}\text{C}$  layer from ITOP and historical Argo observations. The thickness of the  $26^{\circ}\text{C}$  to  $27^{\circ}\text{C}$  layer decreased rapidly as the cap formed, and then more slowly, taking ~25 days to recover to background thickness. c) A summary of potential temperature profiles from selected instruments inside (red) and outside (gray) Fanapi's cold wake. An initially well-mixed layer is capped over, the cap slowly descends into the subsurface wake. Typhoon Chaba then mixes the entire layer about 44 days after Fanapi.

Ambient sound data from 7 floats in 3 storms shows a clear pattern of variation with wind speed (Fig. 4). At low wind speed, the sound level increases with wind at all frequencies, as is well known. However, above about 20 m/s, the sound level begins to decrease, first at the highest frequencies and then, progressively at lower frequencies so that by 45 m/s only, the lowest frequency measured, ~100 Hz, is still increasing. The likely cause of this pattern is the absorption of the higher frequencies by the increasingly dense and deep bubble clouds created by wave breaking at high winds.



**Figure 4. Sound level (dB) as a function of wind speed for 7 float records in 3 tropical cyclones. Only data on the forward half of each storm is shown here. Colors denote different frequencies. The dashed line shows the approximate wind speed at which the sound level at each frequency begins to decrease with increasing wind speed.**

Two papers were published in FY12: An overview article on Typhoons in the Western Pacific and an article led by R.C. Lien, summarizing work done as part of NLIWI in the South China Sea.

## IMPACT/APPLICATIONS

The inability of current remote sensing schemes to detect subsurface typhoon wakes limits the ability of such schemes, and the numerical models that rely upon them for data initialization, to detect such wakes. It seems likely that dynamical models, capable of creating and tracking the wakes over weeks to months, will be necessary.

The regular behavior of sound levels as a function of wind speed suggests that wind speed could be measured by underwater sound on autonomous vehicles operating beneath typhoons and hurricanes.

## PUBLICATIONS

D'Asaro, E., P. Black, L. Centurioni, P. Harr, S. Jayne, I.-I. Lin, C. Lee, J. Morzel, R. Mrvaljevic, P.P. Niiler, L. Rainville, T. Sanford, and T.Y. Tang. 2011. Typhoon-ocean interaction in the western North Pacific: Part 1. *Oceanography* 24(4):24–31, <http://dx.doi.org/10.5670/oceanog.2011.91>

Lien, Ren-Chieh, Eric A. D'Asaro, Frank Henyey, Ming-Huei Chang, Tswen-Yung Tang, Yiing-Jang Yang, 2012: Trapped Core Formation within a Shoaling Nonlinear Internal Wave. *J. Phys. Oceanogr.*, **42**, 511–525. doi: <http://dx.doi.org/10.1175/2011JPO4578.1>

## HONORS/AWARDS/PRIZES